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Microstructure and elevated-temperature shear strength of Zn–4Al–3Mg–*x*Sn high-temperature lead-free solders

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ABSTRACT

The microstructure and shear strength of the high-temperature Zn–4Al–3Mg, Zn–4Al–3Mg–7Sn, and Zn–4Al–3Mg–13Sn solder alloys were investigated in the temperature range of 25–200 °C. The results revealed that the shear yield stress (SYS) and ultimate shear strength (USS) of all three alloys decrease with increasing test temperature. The ternary base alloy showed higher strength levels up to 145 °C, above which all alloys behave similarly. The superiority of the ternary alloy is ascribed to the higher volume fraction of the fine $\alpha-\eta$ eutectic and eutectoid structures and the hard $MgZn_2$ and Mg_2Zn_{11} particles. Introduction of Sn into the base alloy, however, resulted in substantial decrease in the strength, due to the presence of the soft Sn that reduces the volume fraction of the eutectic structure and the hard second phase particles. Despite the weakening effects of Sn, the strength of quaternary alloys is still higher than those of the Zn–Sn and Pb–Sn high-temperature solders.

1. Introduction

Tin-based lead-free solder alloys are considered as suitable substitutes for the toxic tin–lead solders, which have long been used for the joining of electronic devices as well as mechanical components. These tin-based solders are principally considered for intermediate-temperature applications, due to their relatively low melting range [1]. There are, however, some severe thermal environments, in which solders are supposed to withstand higher temperatures and thus new materials with higher melting points are required. For such conditions, various lead-free solders such as Au–Sn, Bi–Ag, Zn–Sn, and Zn–Al based alloys have been proposed to replace the commonly used Pb–Sn alloys containing 85–97 wt.% Pb. The application of Au–Sn and Bi–Ag solders is restricted due to their high cost. On the other hand, the zinc-base Zn–Sn and Zn–Cu–Al alloys have shown strength [2,3] and creep resistances [4,5] which are remarkably higher than those of the conventional Pb–10Sn solder.

Due to the high service temperatures, the high-temperature solder materials should possess reasonable strength that can be attained at elevated temperatures. The ultra-high temperature Zn–Al alloys with relatively high liquidus temperatures of less than 400 °C and solidus temperatures of higher than 370 °C are considered as suitable candidates for the high temperature applications. This family of materials, however, suffers from a relatively low creep resistance at even moderately elevated temperatures [6]. It has been suggested that the addition of different alloying elements to the binary Zn–Al alloy system can modify both soldering and mechanical properties. Addition of Cu enhances hardness and tensile strength [7,8], while Mg and Sn are mainly added for lowering the melting temperature of the base alloy [9]. The detrimental effects of Sn additions on the tensile strength and ductility of Mg–4Al–3Mg solder alloy has been documented. It has been reported that although Sn significantly weakens the alloy, the strength of Zn–4Al–3Mg–6.8Sn alloy at 200 °C is still comparable to that of the Pb–5Sn solder alloy [10].

The strength of the high-temperature lead-free solders are mostly investigated by the conventional tensile test [8,10–12] and in some cases by the shear testing of the joints made on different substrates [13]. Recently, however, the high-temperature shear strength of the bulk Zn–Sn [2] and Zn–Cu–Al [3], and Sn–Sb–Ag [14] solders has been studied by the localized shear punch testing (SPT) technique. There are many reports in the literature indicating that the SPT is an efficient method being capable of producing strength data which are well correlated with those found by the conventional tensile tests [15,16]. This method can be particularly advantageous when the material is available only as small test pieces or there are difficulties with the machining of samples made of very soft materials such as solder alloys. The evaluation of high-temperature strength of the Zn–Al–Mg alloy and its variants by SPT has not been reported before and thus will be attempted in this study.

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2. Experimental procedures

2.1. Materials and processing

This investigation involved three alloys with the nominal chemical compositions of Zn–4Al–3Mg–xSn (x = 0, 7, and 13 wt%). They were prepared from high-purity (99.97%) zinc, tin, and Zn–20Al and Zn–40Mg master alloys, melted in a graphite crucible at 580 °C in an electrical furnace under inert argon atmosphere. Alloys were remelted twice at 480 °C, held at this temperature for 30 min, and then stirred mechanically for 2 min using a stainless steel rod to provide a homogeneous composition. The molten material was then poured into a 16-mm-diameter steel die. The cast bars were cut into 4- and 1-mm thick slices using an electro-discharge wire-cutting machine. The thicker slices were used for microstructural analysis and hardness measurement, and the thinner ones were used for the assessment of shear strength. The specimens were polished with 0.3-mm diamond paste, followed by polishing on an abrasive-free microcloth. Etching was implemented using 20 g CrO_3, 1.5 g Na_2SO_4, and 100 mL H_2O at room temperature. Microstructural examination was carried out for the phase and composition analysis using optical microscopy (OM), scanning electron microscopy (SEM) and X-ray diffraction (XRD).

2.2. Mechanical property measurements

The strength of the materials was assessed by the shear punch testing. The 1-mm thick slices of the materials were ground to a thickness of about 0.7 mm, from which disks of 15 mm in diameter were punched for the SPT. A shear punch fixture with a 3.175 mm diameter flat cylindrical punch and 3.225 mm diameter receiving-hole was used for this experiment. Shear punch tests were performed in the temperature range of 25–200 °C using a screw driven SANTAM universal testing system equipped with a three-zone split furnace. After locating the specimen in the fixture, the assembly of the specimen and SPT fixture were accommodated by the split furnace. Then, the assembly was heated to the test temperature and held for 20 min to establish thermal equilibrium in the testing arrangement before the specimen was deformed by the punch. Tests were run with a load cell of 20 kN capacity and at a constant cross-head speed of 0.25 mm min^{-1}. After application of the load, the applied load P was measured automatically as a function of punch displacement; the data were acquired by a computer so as

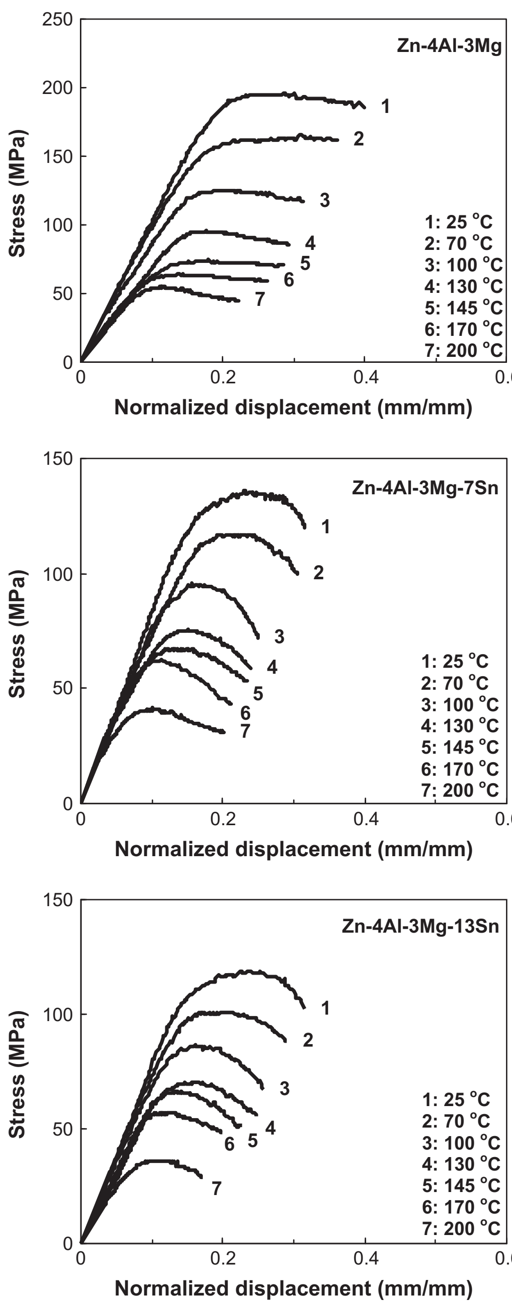

Fig. 1. Shear stress-normalized displacement curves at various temperatures for the tested alloys.

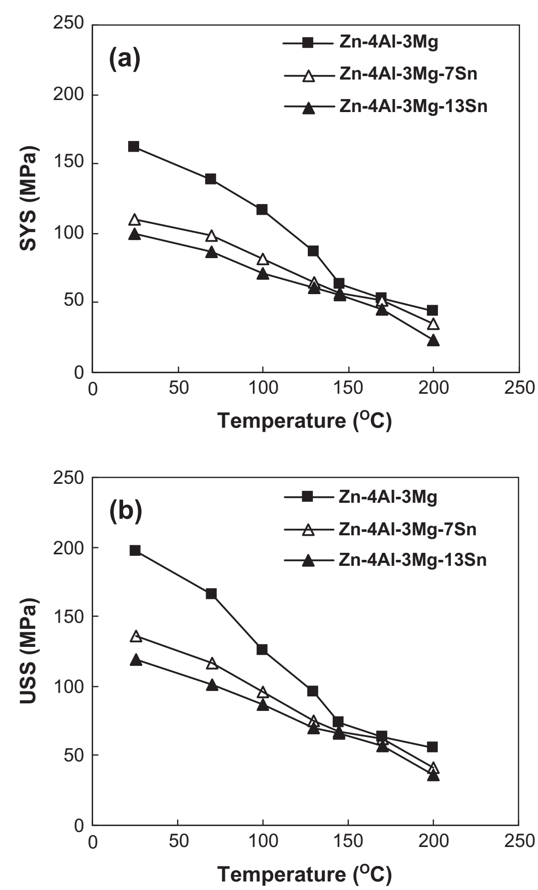

Fig. 2. Comparison of: (a) SYS, and (b) USS of the materials tested at different temperatures.